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Technological performance and alliances over the industry life cycle: Evidence from the ASIC industry

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ABSTRACT

Technology development in firms is frequently based on a combination of internal and external technological learning. Consequently, firms need to develop both technological capital (a patent portfolio) and alliance capital (a portfolio of technology alliances). This paper examines the relationship between technological capital, alliance capital and their joint impact on the technological performance of firms, with an application to the ASIC industry. We find that positive marginal returns to alliance capital are decreasing at higher levels of alliance capital. Technological capital and alliance capital can either augment or reduce each others' influence on innovation performance depending on the stage of the technology life cycle in the industry. A reinforcing relationship related to absorptive capacity requirements and technological uncertainty is present in early stages, while technology leakage and market competition effects render the combination of high levels of technological and alliance capital counterproductive in later stages of the technology life cycle.

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INTRODUCTION

Knowledge is regarded as the single most important resource of firms active in high tech industries (Kogut and Zander, 1992; Conner and Prahalad, 1996; Grant, 1997). The development of technological knowledge bases increasingly relies not only on internal technological strengths but also on knowledge sourced from, or jointly developed with, other firms. In the past two decades strategic technology alliances have received substantial attention as a means to combine internal and external technological capabilities to improve technological performance (e.g. Hagedoorn and Schakenraad, 1994; Shan *et al.*, 1994; Powell *et al.*, 1996; Mitchell and Singh 1996; Stuart, 2000; Laursen and Salter, 2006). Increasing R&D costs, growing sophistication of technologies, and the potential of emerging technologies to undermine the competitive positions of incumbents, have spurred the growth of 'learning alliances' through which companies can speed up their capability development and exploit knowledge developed by others (Grant and Baden-Fuller, 1995, 2004). Market transactions are generally considered to be a weak alternative to alliances as most valuable knowledge is cumulative and tacit in nature. This specific nature makes it hard to transfer knowledge between organizations through market transactions (Mowery, 1988; Mowery *et al.*, 1995; Osborn and Baughn, 1990).

A growing number of studies have investigated the impact of portfolios of technology alliances on firm performance (Hagedoorn and Schakenraad, 1994; Shan *et al.*, 1994; Powell *et al.*, 1996; Mitchell and Singh 1996; Stuart, 2000; Sampson, 2007; Jiang et al., 2010). Other studies have examined the role of internal technological capabilities and technology portfolios on firms' innovation performance, with particular attention to the role of technological diversification (e.g. Leten et al., 2007; Henderson and Cockburn, 1996; Breschi et al., 2003; Patel and Pavitt, 1997; Katila and Ahuja, 2002; Stuart and Podolny, 1996; Nerkar and Roberts, 2004). Yet, these two sources of technological capability building, internal technological development and external technological learning, have to be considered jointly in their impact on technological performance. The seminal contribution by Cohen and Levinthal (1990) suggests that internal technological capabilities are a prerequisite for a sufficient absorptive capacity necessary to understand, absorb, and effectively utilize externally acquired know-how. Internal technology development is increasingly interwoven with the external sourcing of technologies and they are often seen as mutually reinforcing each other's effect on the rate of innovation of a company (Cohen and Levinthal, 1990; Lane and Lubatkin, 1998; Duysters and Hagedoorn, 2000; Van de Vrande *et al.*, 2006). This suggests that internal technological capabilities strengthen the impact of alliance portfolios (Lane and Lubatkin, 1998; Cassiman and Veugelers, 2006). On the other hand, companies with strong internal technological capabilities may have least to gain from external technology sourcing, and most to loose from asymmetric learning benefits accruing to alliance partners (e.g. Khanna et al, 1998; Ahuja, 2000a). Surprisingly, there are no large-sample empirical studies that analyze the potential joint effects of internal and external knowledge acquisition on the technological performance of firms.[1]

In this paper, we investigate the relationship between the technological performance of firms in high-tech industries and their internal technological capital and technology alliance portfolios. Drawing on the extant literature on technological learning, the resource based theory of the firm, and theories of strategic alliance formation, we develop hypotheses on the nature of these relationships. We show that the joint and interactive performance effects of technological capital and alliance capital depend crucially on the technology life cycle.[2] A reinforcing relationship related to absorptive capacity requirements and technological uncertainty is present in early stages while technology leakage and market competition effects render the combination of high levels of technological and alliance capital counterproductive in later stages of the technology life cycle.

We test hypotheses on a longitudinal dataset covering technological activities, alliance strategies, and financial data on the population of producers of ASICs (application-specific integrated circuits) in the period 1987-2000. The ASIC industry and its development over time is an interesting case to study, given the importance of technology driven competition and the myriad of technology alliance relationships in the sector. Our dataset covers all ASIC-producers over the most important phases of the technology life cycle characterizing the sector: from an early stage of rapid technology development under uncertainty in the 1980s to a mature stage in the later 1990s exhibiting incremental improvement of established technologies and intensifying competition.

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1 A partial exception is Ahuja (2000a) who focuses on the impact of technical, commercial and social capital of firms on the formation of new alliances. Commercial resources are those required to convert technical innovations to products and services. In our research we focus on technological performance and abstract from commercial capabilities.

2 We are indebted to an anonymous referee for the suggestion to focus on changing relationships between the variables of interest over time.

THEORETICAL BACKGROUND AND HYPOTHESES

Drawing on the resource based view of the firm, we first establish a baseline hypothesis on the relationship between technological capital – which we conceptualize as past technological performance - and subsequent technological performance. We then discuss the relationship between alliance capital and technological performance. Finally we develop the hypotheses on the changing interaction between alliance capital and technological capita in the context of developments over the technology life cycle.

Technological capital

Over the past two decades, the resource-based view of the firm has gradually become one of the most influential theoretical perspectives in the field of strategic management (Wernerfelt, 1984; Barney, 1991; Teece *et al.*, 1997; Ahuja and Katila, 2004). The resource based view holds that resource heterogeneity is an important source of performance differentials among firms. Knowledge assets are seen as a major source of such resource heterogeneity (Kogut and Zander, 1996; Spender, 1996). A core premise of the knowledge-based view of the firm is that knowledge assets accumulated over time constitute the source of a firm's sustainable competitive advantage in the marketplace. Firm-specific knowledge assets are of strategic interest because they are rare, imperfectly tradable and hard to imitate as long as part of the technological know-how is tacit in nature. The cumulative development over time of technology-related knowledge assets leads to what we label "technological capital" and is a function of past successful technology development activities. The development of this firm specific technological knowledge is time and resource consuming and as a result usually difficult to imitate by (potential) competitors. Moreover, building up technological capital bares substantial risks given the large up-front R&D costs involved while the technological and commercial outcomes may be highly uncertain (Mitchell and Singh, 1992). Because of the cumulative character of technology development, the current technological position of a company is shaped by its past technological activities (Nelson and Winter, 1982; Coombs and Hull, 1998; Teece *et al.*, 1997; Teece, 2007). Previous investments and strategic choices and their subsequent technology development outcomes determine the current position of a firm and shape its future technology options. Companies that have built up specific technological capital successfully in the past ahead of their rivals are expected to maintain a technological lead, as lagging firms are less likely to be able to catch up through internal technology development (Shan, 1990; Podolny and Stuart, 1995; Stuart *et al.*, 1999; Cefis, 2003, Roper and Hewitt-Dunas, 2007). Firms with accumulated technological capital based on past technology development successes are likely to be able to maintain superior technological performance, which in turn leads to a further accumulation of technological capital.[3] This suggests the following baseline hypothesis:

(Baseline) Hypothesis 1: *Technological performance of a firm is a positive function of its technological capital (cumulative past technological performance)*

Alliance capital

The resource based view of the firm has also been instrumental for the analysis of strategic alliance formation, as there is growing consensus that the rise in the number of strategic technology alliances has been driven by resource interdependence and complementarities (Pfeffer and Nowak, 1976; Nohria and Garcia-Pont, 1991; Nooteboom *et al.*, 2007). A central position in a network of technology alliances has been recognized as a distinctive and important form of capital of innovative companies (Dyer and Singh, 1998; Gilsing, 2008; Gulati, 1995, 1999). In this study, we term the firms' existing portfolio of technology alliances its 'alliance capital'. Particularly in rapidly changing technological fields, internal R&D efforts need to be complemented by external means of technology acquisition (Tyler, 2001). The creation of a strategic technology alliance network can facilitate the access to technological resources across industries or technological fields. Alliances are often used by companies as instruments to acquire technological knowledge and to develop new skills that reside within the partnering companies (Hamel, 1991; Hagedoorn and Schakenraad, 1994; Srivastava and Gnyawali, 2011). Previous research has established that technology alliances often have a positive impact on the technological performance of companies (Baum and Oliver, 1991; Mitchell and Singh, 1996; Uzzi, 1996; Powell *et al.*, 1996; Hagedoorn and Schakenraad, 1994; Rothaermel and Deeds, 2004).[4] Technology alliances can ease a number of transactional and contractual differences (Williamson, 1975, 1985; Jarillo, 1988), enable firms to scan their environment for new windows of opportunities and promising new

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3 An exception is the case of severe instability in the prevailing technological paradigm due to the rise of competence destroying breakthrough technologies (Abernathy and Clark, 1985; Christensen, 1997; Christensen and Raynor, 2003), which makes it difficult for firms to build on their previously developed knowledge base.

4 A notable exception is the work of Stuart (2000) who found no significant relationship between the number of alliances and the rate of innovation of semiconductor firms.

technologies (Duysters and de Man, 2003), and lower the risks and costs of developing new technologies in-house (Faems et al, 2005).

On the other hand, research on interorganizational networks in general and technological alliance networks in particular has also pointed out that involvement in a broad range of alliances may lead to saturation and overembeddedness in the network (Kogut *et al.*, 1992; Uzzi, 1997). This is, in particular the case when firms are involved in strong-tie relationships (Granovetter, 1973). A strong inter-firm network can lead to inertia that holds firms back from severing ties with existing partners and/or from entering into other and potentially more successful alliances. This may be due to an implicit expectation of loyalty to alliance partners and pressure from their partners to replicate ties within the group (Gulati et al., 2000; Gilsing and Lemmens, 2004). Nahapiet and Ghoshal (1998, p. 245) argue that the collective alliance capital resulting from dense networks can limit a firm's openness to information and to alternative ways of technology development, which can lead to a "collective blindness" that may have detrimental effects on technological competitiveness. Embeddedness in existing technology partnerships can create a dependence that increases the likelihood of a company falling in the so-called familiarity trap (Ahuja and Lampert, 2001)[5]. It is argued that experience and competence in a specific set of technologies leads to the emergence of a dominant logic (Prahalad and Bettis, 1986) and an increasingly rigid view on technological capabilities (Leonard Barton, 1992). This, in turn, reduces the probability of a company's willingness to experiment with other problem solving approaches. This absence of experimentation reduces the chance that a company will discover new technological opportunities in high tech industries (Jaffe, 1986; Lunn and Martin, 1986; Levin *et al.*, 1985, Sampson 2007).

As the benefits of further expanding the alliance network may be limited, likewise the costs of allying can increase substantially in the number of alliances. Gomes-Casseres (1996) has shown that there is an upper-limit to the number of alliances that a company can manage successfully. Alliance management draws on the same, scarce, managerial resources and management attention and management also has to coordinate across alliances (Harrigan, 1985; Hoang, 2001). Management attention and integration costs may grow exponentially

5 Learning traps (Levinthal and March, 1981, 1993) embody the conflict between routines that enable the organization to perform well in the short run but may position the organization unfavorably for the future (Ahuja and Lampert, 2001: 523).

beyond a certain number of alliances (Duysters and de Man, 2003; Duysters et al, 2012) and a firm's effectiveness at managing its alliances will decline with the number of alliances it maintains (Deeds and Hill, 1996, Hoang, 2001). Larger technology alliance portfolios increase the risks of dealing with various, often unfamiliar streams of knowledge that are increasingly difficult to integrate (Grandstrand, 1992; Ahuja and Katila, 2004; Vanhaverbeke *et al.*, 2009). Hence, a firm can start to suffer from information overload and diseconomies of scale. A second reason for increasing costs of alliances is that unwanted knowledge spillovers and free rider effects are likely to increase as the number of alliance partners grows. More partners implies more potential free-riders or 'recipients' of spillovers while, at the same time, resources and management time to monitor this need to be spread over a larger number of partnerships. This implies that fewer managerial and R&D resources can be freed to focus on absorption and integration of technology developed within the alliances.

The above arguments suggest that an increase in alliance portfolio size at some point will lead to reduced marginal benefits and effectiveness of additional alliances, whereas the extra costs of adding new alliances will increase. As a result, we expect an inverted-U shaped relationship between a firm's existing stock of alliances (its alliance capital) and its technological performance.

Hypothesis 2: *The alliance capital of a firm (i.e. the number of prior technology alliances) has an inverted-U shaped effect on its technological performance.*

Alliance capital, technological capital and the technology life cycle

Technological learning is increasingly based on a combination of internal and external learning (Laursen and Salter, 2006; Chesbrough 2003; Chesbrough et al. 2006). Both types of learning have been described in the literature as complements, specifically because external technology sourcing requires a sufficient level of internal R&D capabilities, i.e. absorptive capacity (Cohen and Levinthal, 1990; Duysters and Hagedoorn, 2000; Cassiman and Veugelers, 2006; Arora and Gambardella, 1990). Firms that are capable of proper valuation and assimilation of external knowledge are more likely to profit from a strategy to enter into technology alliances and develop a broader internal technology base to reap the benefits of external technological learning (Mitchell and Singh, 1996; Lane and Lubatkin, 1998, Lane, Koka, & Pathak, 2006). They may also have a greater ability to identify and evaluate the technological capabilities of specific potential partners, selecting on complementary expertise and reducing the risk associated with difficulties in selecting partners (Prabhu, Chandy and Ellis, 2005). These arguments suggest a positive interaction between technological capital and alliance capital, as they reinforce each others' effect on technological performance.

On the other hand, there are arguments suggesting that combining alliance capital and technological capital may be detrimental for technological performance. Firms with strong and unique internal technological capabilities are likely to have abundant alliance opportunities. These firms are attractive to other firms that expect to benefit from access to these capabilities through alliances (Baum *et al.,* 2000). However, at the same time, firms with strong internal capabilities are less likely to reap benefits from alliances in terms of an expected improvement in their own technological performance (Ahuja, 2000a), since firms possessing leading edge technological competences have less to learn from alliance partners (Kale and Singh, 1999; Khanna *et al.,* 1998). Firms that are well endowed with technological competences may therefore receive alliance proposals of which the marginal benefits are relatively small. While technologically leading firms should be more selective in evaluating those proposals to focus on rent generating alliances, managers have to deal with imperfect information and may establish alliances that provide asymmetric learning benefits to their alliance partners. This risks generating and/or strengthening technology competitors in the future and eroding the firm's technology lead and first-to-patent performance **(**Hamel *et al.*, 1989, Jiang et al., 2010). Second, the larger a firm's alliance network in combination with abundant accumulated technological capital, the more likely that internal and external knowledge development will overlap, and that, at a particular level of internal technological capabilities, the costs of setting up and managing additional alliances will be higher than the benefits (Harrigan, 1985, Duysters and Lokshin, 2011). These arguments suggest that stronger internal capabilities may decrease the benefits of expansion of alliance portfolios.

The interaction between technology and alliance capital over the technology life cycle

The role of the contrasting influences of combining technological and alliance capital on technological performance is likely to depend on the stage of the technology life cycle. Technology life cycles comprise of early stage search for the most effective technologies in the context of abundant technological opportunities in the domain (Klevorick et al, 1995; Abernathy and Utterback, 1978; Andersen, 1999; Schmoch, 2007). This is associated with entry by established and new firms attracted by these technological opportunities and perceived commercialization potential (Breschi et al., 2000). Once technological paradigms have been established and barring instability of the paradigm (Abernathy and Clark, 1985; Christensen, 1997; Christensen and Raynor, 2003), technological development efforts focuses on incremental improvements. Given the cumulative, path-dependent process of technology development, accumulated technological capital capabilities established over time by the most successful firms weigh heavily in concurrent performance (Dosi, 1982).

In the early stages of the technology life cycle, many firms are lacking a sufficient internal knowledge base and have yet to establish proper routines to value and assimilate external knowledge. The firms that succeed in developing these resources are much more likely to learn effectively from technology alliances and reap the benefits of building up alliance capital (Mitchell and Singh, 1996; Lane and Lubatkin, 1998, Nooteboom *et al.*, 2007). Given that technology developments are still uncertain and subject to sudden change, broad technology search is of eminent importance and firms with capabilities to recombine knowledge from external technology sourcing and internal technology development are particularly well placed to record strong technological performance. This implies that the -absorptive capacity- argument suggesting a positive interaction effect between technological and alliance capital is likely to weigh heavily in the early stages of the technology life cycle.

In contrast, in later stages of the technology life cycle, most firms have built up absorptive capacity through cumulated technology development efforts such that absorptive capacity is less a distinctive resource to reap the benefits of strategic technology alliances. At the same time, technology development efforts focus on incremental and cumulative improvements, benefitting firms that are already leading in terms of the technological competition. In particular those firms that have been successful in the past, building up appreciable levels of technological capital, are less likely to benefit from technology alliances. The firms may have abundant alliance opportunities as attractive collaboration partners, but they are most likely to suffer from unwanted and unintended technology leakage effects. In these later stages of the technology life cycle, competitive forces have intensified and firms with smaller technological resources will be trying to catch-up technologically by teaming up with competent partners. These firms may use a cooperation strategy in order to leapfrog existing firms by drawing on the incumbent firm’s technological knowledge. With little expected benefits, increased risk of losing technological advantages and the costs of effective alliance portfolio management and integration, relying on alliance capital strategies is likely to be counterproductive for firms with abundant technological capital. Hence, the arguments suggesting a negative interaction effect between technological and alliance capital are expected to be have substantial force in the later phases of the technology life cycle.

Collectively, the above arguments suggest that the interactive effect of technological and alliance capital on technological performance depends on the stage of the technology life cycle, with an initial positive interaction turning into a negative effect in the later stages of development. This suggests the following hypothesis:

Hypothesis 3: *Alliance capital and technological capital reinforce each others' effect on technological performance in the early stages of the technology life cycle. This positive interaction gradually disappears and can turn into a negative relationship in later stages of the technology life cycle.*

EMPIRICAL SETTING

Our hypotheses are tested on the population of ASIC-producers that were active in the period 1987-2000. ASICs - i.e. application-specific integrated circuits - are a special type of ICs (integrated circuits) that accounted for about 12 % of worldwide IC sales in 1995. In contrast with the general purpose ICs such as DRAMs and microprocessors, ASICs are built to perform only one particular function – e.g. converting digital signals of a CD or MP3-file into music (Dibiaggio, 2007; Einspruch and Hilbert, 1991). In the early 1980's, the use of layout structures and the adoption of physical synthesis in semiconductors led to the birth of the ASIC industry. In the late 1980's, the adoption of logic synthesis fundamentally changed the way in which most ASIC-designers approached their task. By the early 1990's a dominant approach to ASIC design was established and in technological terms ASIC development entered a more stable period in the 1990s. The period 1987-2000 captures part of the volatile years of the ASIC industry as well as the period of maturing technologies and intensifying competition.

The ASIC market is a typical high-tech industry where technology is the driving force shaping competition among firms. R&D-to-sales ratios are exceptionally high with ratios greater than 10 percent no exception. The ASIC market is divided into three submarkets. According to the "Integrated Circuit Engineering Corporation" (ICE) the ASIC market includes the following categories of ICs: gate arrays (GA), full custom ICs (FC), and programmable logic devices (PLDs). Formal definitions are given in Table 1.

Insert Table 1

A wide range of specific system functions can be fabricated alternatively by gate arrays, full custom devices or PLDs. These three ASIC-categories are different devices realising the same system functionalities. As a result, there is almost no affinity between the targeted system function and the type of ASIC to use. The only exception is linear arrays, which are used to design analog or mixed (analog/digital) system functions. Linear arrays are applied mainly in the telecommunication and consumer electronics markets, where most signals are analog in nature. ASIC vendors typically have to make a choice between the three ASIC types minimizing the volume-dependent total cost per chip. PLDs are the cheapest solution for low volume ASICs. Once the production volume exceeds the level of a few thousands units, gate arrays become the most interesting ASIC solution. Custom ICs are the most efficient solution for production volumes that exceed several hundred-thousands of ASICs (Stolwijk et al., 2012).

The development and production of ASICs requires the interplay between different economic agents. The most important participants are the ASIC design houses, IC manufacturing facilities, electronic system manufacturers and CAD-tool vendors. This list can be enlarged by a number of auxiliary and/or intermediate players, such as companies offering services in the microelectronics field, firms that translate customers' needs into the specifications for the design of ASICs, and university labs. Electronic system manufacturers usually build a foothold in the ASIC market by vertical integration: they want to achieve a competitive advantage for their electronic systems through proprietary ASIC designs. Electronic system manufacturers also make corporate-wide deals and second-source agreements with foundries. Large system manufacturers have their own ASIC design house and foundry or they acquire one. Vertically integrated system manufacturers still cooperate with specialised design houses because of recurrent peaks in design work. Large, integrated electronic system manufacturers have their own fab-lines. Their ASICs are processed together with standard ICs. Smaller companies set up agreements with different foundries to process their ASICs. Second-source agreements are frequently used in order to ensure availability of ASICs on time and to avoid lock-in situations. Captive producers - e.g., IBM and DEC - also establish second-source agreements because of peaks in demand. For complex ASIC-designs companies establish numerous joint development and cross-licensing agreements (Vanhaverbeke et al. 2002), with technology alliances focused on keeping up with the latest technologies (Duysters and Hagedoorn, 1996).

The role of alliances in the ASIC-industry changed however over time. In the 1980's the industry was still in its infancy. The adoption of physical synthesis, which gave birth to the ASIC industry, and the adoption of the logic synthesis later in the 1980's (FPGA) turned the eighties in a highly volatile period for ASIC producers. It was a period characterized by high technological uncertainty. Technology alliances focused on new approaches to increase functionality, and technologies were changing rapidly in the absence of a dominant approach. By the end of the 1990's, the ASIC technology has been well established and was even considered to be mature (McClean, 2001). The market turbulence and the rapid technological development of the early days were replaced by established applications building on known technology solutions for particular customer requirements. Technological development focused more on process design as time to market considerations - guaranteeing that customers' products get to the market on time – became a crucial competitive consideration.

DATA, VARIABLES AND MODELING

Data sources

Our panel dataset covers the population of ASIC producers over the period 1987-2000. This specific period was characterized by strong growth and high technological turbulence. This is probably the most salient phase in the history of the ASIC industry. Based on ASIC patent data from the USPTO, strategic alliance data from the MERIT-CATI database on technology alliances (Duysters and Hagedoorn, 1993), and ASIC industry reports, we identified 117 firms active as ASIC producers during that period, which resulted in an unbalanced panel of 1190 observations.

The data on strategic alliances relate to alliances of which the major focus is on technological developments in the ASIC-industry. In the CATI database only those types of inter-firm agreements are being collected that contain arrangements for transferring technology or joint research and development. Mere production or marketing agreements are excluded on the basis of the description of the alliances in the public sources, which are used as a basis for the database. Descriptions were checked manually for each alliance. During the period 1982-2000, 643 ASIC-related strategic technology alliances were identified. Alliance activity grew to a first peak in the mid-eighties, followed by a decrease in the late eighties and the early nineties. More alliances were established again in the period 1994-2000.[6]

Insert Figure 1

Strategic alliances in the ASIC industry consist of non-equity agreements of which the majority is joint development agreements. Joint ventures are the most important form of equity alliances. Our measures of technological performance and technological capital draw on patent data from the US Patent Office.[7] In particular in industries where companies operate on a global scale, such as the ASIC-industry, U.S. patents are a good proxy for companies' worldwide technological performance and technological capital. Financial data of ASIC producers have been gathered from different sources among which the annual ICE reports (McClean, 1985-2001). The data contain the ASIC-sales, the distribution of the ASIC-sales across the three segments, and the R&D-intensity on the corporate level for these companies.

Variable definitions and operationalization

To test the hypotheses we constructed a number of variables. Table 2 shows the variable definitions.

Insert Table 2

The dependent variable, *technological performance*, is often operationalized by the rate at which patents are granted to innovating firms. However, patents are not equal in value. Some patents refer to basic knowledge at the core of a technology, while others are merely of incremental value. The technological importance of innovations can be estimated with the help of patent citations (Albert *et al.*, 1991; Narin *et al.*, 1987), with the value of patents increasing in the number of citations received. Hence, our dependent variable is the number

6 It would have been of interest to analyze the earlier years in the 1980s. However, because of a lack of industry information in the early 1980s and our use of alliance and technological stocks (build up over a 5 year period), the first year we observe the (lagged) independent variable for identified sample firms is 1987.

7 The patents were selected by means of a query on 'ASIC' and related concepts/definitions such as 'gate array', 'linear array', 'FPGA', 'PLD', 'full custom', 'SPGA' and 'EPAC'. Patents can be categorized by means of the International Patent Classification, an internationally recognized hierarchical classification system comprising 118 broad sections and 624 subclasses nested within the classes. It is furthermore possible to subdivide the subclasses into 67.000 groups. ASIC-related patents are classified in a relatively small set of subclasses (75 in total).

of patents that are yearly granted to a company weighted by the number of citations. In order to correct for right censoring we estimated the number of citations patents would receive over their life-span, based on the number of citations they received using Hall *et al.*'s (2001) simulated cumulative lag distribution tables. The NBER citations database was used to determine patterns of citations (Hall *et al.*, 2001). We adopted a nonlinear weighting scheme, assuming that the marginal informational content increases with the number of citations, as suggested in Trajtenberg (1990). We counted a patent grant as technological performance in the year the company applied for the patent. The dependent variable thus measures the number of patents that a company successfully applied for in a particular year weighted by their received citations[8].

Explanatory variables

Technological capital (cumulative past technological performance) is calculated as the number of ASIC-related patents that an ASIC-producer successfully applied for in the five years prior to measured technological performance. Patents granted to a company are a good measure of the technological competences of a company (Narin *et al.*, 1987) in industries where the propensity to patent inventions is relatively high (Arundel and Kabla, 1998) and extant research has used patent stock variables to represent cumulative knowledge bases (e.g. Leten et al., 2007; Vande Vrande et al. 2011). As with the dependent variable, we weigh patents with the number of citations they receive, using a nonlinear weighting scheme. Studies of R&D depreciation (Griliches, 1979, 1984) suggests that knowledge capital depreciates sharply, losing most of its economic value within 4-5 years. A moving window of 5 years is therefore the appropriate time frame for assessing the impact of technological capital in high-tech industries (Podolny and Stuart, 1995; Stuart and Podolny, 1996; Ahuja, 2000a). The inclusion of the stock of technological capital reflects the notion that the flow of new technology creation builds on the existing knowledge and technology stock, while the new technologies subsequently add to this cumulative knowledge and technology stock. We scale the variable by dividing it by 1000.[9]

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8 Our weighting scheme uses patents that have been granted by the U.S. Patent Office before the end of 2000. Since the observation period is 1988-2000, there is no strong bias at the end of the period, as most patents are granted within a period of 2 to 3 years. Of all ASIC patents in our sample only 3.6% were granted after 4 years.

9 Scaling does not affect the empirical results but facilitates the presentation of estimated coefficients, which otherwise would become very small. As technological capital has partial properties of a lagged dependent variable, its coefficient will also reflect a range of unobserved firm-specific characteristics that allowed for effective technology accumulation.

Following Gulati (1995), we computed *alliance capital* by counting all technology alliance activities of the ASIC-producers prior to the year in which we measure technological performance. We opted for a moving window approach, assuming that only 'ongoing' alliances have an impact on the technological performance of the focal firm. Alliances, for which we observe termination within the observation period 1987-2000, are assumed to have an impact on the rate of innovation as long as they were not terminated. For the other alliances we assume that the lifespan of alliances is five years. This five-year window follows conventional assumptions in alliance network research (Kogut 1988, 1989; Gulati, 1995, 1999; Stuart, 2000; Lavie, 2007). We include the linear term and the squared term of alliance capital. Hypothesis 2 predicts a positive coefficient for the former and a negative one for the latter.[10]

Finally, in order to test Hypotheses 3, we 1) create the interactive term of technological capital and alliance capital, 2) allow the coefficient of the interactive term to vary with the stage of the technology life cycle by multiplying it with a trend term (taking the value 0 in 1987). Hypothesis 3 suggests a positive interaction term evaluated in the earliest year of development of the ASIC industry in our sample (hence a positive main effect), and a negative effect of the interactive term if multiplied with the trend term reflecting the change of sign of the interaction in later years of the technology life cycle.

Control variables

Following the arguments of Stuart (2000) and Baum *et al.*, (2000) that the technological (and economic) performance of companies is not so much determined by the size of the alliance network but rather by the characteristics of the focal company's alliance partners, we control for the technological strength of the firm's alliance partners. Stuart (2000) finds evidence that alliances with partners that are technologically well endowed have a larger positive impact on post-alliance performance of the focal firm. We measure the alliance partners' technological strength as the citation-weighted number of successful patent applications of the partners in the 5 years preceding the alliance. We scale the variable by dividing it by 1000.

We include two time-variant firm-specific control variables: the natural logarithm of firms' ASIC sales and R&D intensity. Large and R&D intensive companies possess more R&D

[10] Alternatively, applying a weighting scheme for alliance based on the expected importance of alliance strength (e.g. with joint research receiving a higher weigh than cross licensing arrangement) produced very similar empirical results.

resources and may be more likely to benefit from economies of scale and scope in the process of R&D, improving technological performance (e.g. Leten *et al.*, 2007; Pakes and Griliches, 1984; Hall, *et al.*,2001; Griliches, 1984, 1990). We also include a range of dummy variables to control for origin and type of firms. Firms can be involved exclusively in the production of gate arrays, standard cells or PLDs, or they can be involved in more segments at the same time. Segments are important in the sense that firms in each segment face different types of technologies, different competitors and different competitive or technological dynamics. We include a set of 6 dummy variables depicting the different segment combinations, with PLD manufacturers as reference group. We also include dummy variables controlling for the home region in which the firms are based. Firms from different home regions may for instance differ in their propensity to patent (in the US). We include dummies for headquarters based Asia or Europe, with North-America as reference group. A last dummy variable is included to control for possible biases due to the fact that some large companies produce ASICs only for their internal needs (captive market), i.e. for internal supply to their electronic systems operations. These captive producers are a small minority of ASIC-producing companies but are nonetheless important in terms of technological capabilities (e.g. IBM).

Finally, we include annual dummy variables to capture changes over time in the propensity of firms to patent their inventions, as the number of ASIC-technology related patents increased from 50 in 1987 to 451 in 2000. Part of this growth is the result of the growing importance of ASIC-products and the accelerating changes in this technological field. Moreover, firms have become increasingly aware of the earnings they can reap by improving intellectual property management and patenting strategies (Grindley and Teece, 1997; Teece, 1998; Rivette and Kline, 2000).

Model specification and econometric issues

The dependent variable is a count variable - i.e. the weighted number of patents a firm successfully filed for in a particular year. A Poisson regression approach provides a natural baseline model for such data (Hausman *et al.*, 1984; Henderson and Cockburn, 1996). A Poisson regression however assumes that the mean and variance of the event count distribution are equal and in particular for panel data this assumption is likely to be violated with overdispersion as the norm. In the case of our dependent variable, technological performance, the variance vastly exceeds the mean and a statistical test confirms overdispersion.[11] Instead, we used a random effects negative binomial regression model which allows for the variance to exceed the mean. The random effects specification controls for unobserved heterogeneity among firms, such that the coefficients of the alliance variables are likely to reflect the impact of differences in alliance strategies and not the effect of correlated but omitted unobserved firm characteristics.[12]

RESULTS

Table 3 presents descriptive statistics and the correlation matrix of the variables. The correlations between the independent variables are not excessively high, apart from the definitional correlations between alliance capital and its squared term on the one hand and alliance capital and technological capital with the interaction term (and the trend-moderated interaction term) on the other hand.

Insert Table 3

Table 4 presents the results of the random effects negative binomial model explaining yearly technological performance (citation weighted ASIC patents) of the ASIC producers. Model 1 in Table 4 is a baseline model omitting the hypothesis testing variables. Model 2 adds technological capital, and model 3 introduces alliance capital related variables. Model 4 included the interaction term between technical and alliance capital, while in model 5 the trend term-moderated interaction effect is included. In model 1, firm size and R&D intensity are significantly positive. The technological performance of alliance partners also has a positive and significant effect on technological performance, in accordance with previous research (Stuart, 2000; Baum et al, 2000). European producers show a lower level of technological performance than US firms, ceteris paribus, and there are also significant differences between the types of ASIC producers. Adding technological capital in Model 2 improves the overall fit and significance of the model. Technological capital has a highly significant impact on technological performance in line with our baseline Hypothesis 1. Adding the alliance capital variables in Model 3 increases the significance of the model further and generates an expected reduction in the coefficient of the technological capital of

[11] The likelihood ratio test for overdispersion in the panel Poisson model confirmed overdispersion at the 0.0001 significance level.

[12] Hausman tests suggested insignificant differences between the estimated coefficients in random effects and fixed effects models, with the latter producing very similar results. Hence we present result with the more efficient random effects estimator.

alliance partners. The linear effect of alliance capital is positive and the quadratic term is negative, supporting Hypothesis 2 and suggesting an inverted-U shaped relationship between alliance capital and technological performance.

Insert Table 4

In model 4, the interaction effect between alliance capital and technological capital is significantly negative, suggesting that on average over the period of analysis (1987-2000) investing in alliance capital is counterproductive for firms with high levels of existing technological capital (and vice versa). Once this interaction term is allowed to differ by the stage of the technology life cycle by introducing the moderation effect of the trend term, the interaction term turns significantly positive, while the trend moderator term is significantly negative. This confirms Hypothesis 3, and indicates a positive interaction effect in the earliest year of our analysis (1987), which gradually declines and turns negative in the later years. Inspection of the coefficients shows that the turning point (from positive to negative) is around 1994.

In order to examine the effects of combining technological and alliance capital more precisely, we have to take into account all relevant coefficients. The joint impact of both types of capital on technological performance is visualized in figures 2a and 2b. The figures show predicted effects based on the estimates in model 5 for the years 1987 and 2000, which represent an early and a late year in the technology life cycle. The graphs are drawn for the 95% intervals of technological and alliance capital in those respective years, which reflects the evolution of technological and alliance capital over the technology life cycle.[13]. Figure 2a plots the mean predicted technological performance as a function of technological capital and alliance capital in 1987. The figure shows that in this year ASIC firms could improve their technological performance by combining technological capital and external technology sourcing through technology alliances. Relying solely on alliance capital does not improve the innovation performance considerably – as is illustrated in Figure 2a when alliance capital increases while technological capital is kept at low values. Combining strong technological capital with an increasing number of alliances leads to much higher performance levels,

[13] The predicted values of technological performance include the effects of the other control variables (at the sample mean in the specific year) and the average random effects. The technological performance dimension is displayed on a similar scale in the two figures to enable comparison.

illustrating that alliances and technological capital reinforce each others' effect on technological performance in the early stages of the technology life cycle, as predicted in hypothesis 3. Figure 2b shows predictions for the year 2000. This figure displays a typical saddle point form, where either technological capital or alliance capital pays off, but with combinations of large stocks of technological capital with an extensive network of alliances detrimental for technological performance. While firms with small stocks of technological capital benefit from establishing alliances, established firms with larger technological capital only benefit from extending internal technological capita. The graph illustrates how in later stages of the technology life cycle the absorptive capacity advantages are arpparently outweighed by the risks and costs of combining large bases of technological and alliance capital, as argued in hypothesis 3.

Insert figures 2a and 2b

DISCUSSION AND CONCLUSIONS

The increasing requirements for successful innovation in high tech industries have forced companies to establish multiple technology alliances. Internal technology development is increasingly interwoven with the external sourcing of technologies and they are often seen as mutually reinforcing each other's effect on the rate of innovation of a company (Cohen and Levinthal, 1990; Lane and Lubatkin, 1998; Duysters and Hagedoorn, 2000; Van de Vrande *et al.*, 2006; Laursen and Salter, 2006; Chesbrough 2003).

In this study we argued that there are good reasons to suggest that technological capital and alliance capital may be either be complements or substitutes, depending on the stage of the technology life cycle of the industry. On the one hand, firms with strong internal technological capabilities will be better able to assimilate and integrate external technology as suggested by the literature on absorptive capacity. Firms with well-developed technological capital may also have the ability to better identify and evaluate the technological competences of external partners, reducing the hazards associated with selecting technology partners. On the other hand, firms with strong technological capabilities may reap fewer benefits from alliances. They have less to learn from their alliance partners and risk creating competitors when they establish alliances that provide asymmetric learning benefits to their alliance partners. In addition, firms combining strong internal capabilities and an extensive alliance portfolio are more likely to face overlaps in technology development efforts, while they have to invest substantial managerial and R&D resources in alliance efforts that are perhaps more efficiently invested in-house. We argue that the net impact of these forces is dependent on the state of development stage of the technology in the industry. In the early phases, absorptive capacity is crucial and alliances are needed to perform broad technology search under technological uncertainty and the absence of an established technological paradigm, suggesting a positive interaction. In the later phases of the technology life cycle of the industry, technologies and resource bases are established while technological development is more incremental and predictable. Absorptive capacity is much less of a crucial differentiator for success, while the leading firms with the largest technological capital bases face increasing competitive threats from technological followers in the industry. Under such circumstances the negative effects of combining technological and alliance capital outweigh the positive effects.

Our analysis of technological performance in a longitudinal study of ASIC producers confirmed that technological capital and alliances are complements and mutually beneficial in the early years of the technology life cycle. There are decreasing marginal benefits of large alliance portfolios, but firms with strong internal technological capital bases are better able to avoid such declining benefits and are better able to efficiently operate larger alliance portfolios. Technological capital and alliance capital do not only have a positive independent effect on innovation performance, they also reinforce each other's effect on technological performance. In contrast, in the later years of the ASIC technology life cycle, the interactive effect of technological and alliance capital gradually turns negative, as the absorptive capacity advantages are outweighed by the risks and costs of combining large bases of technological and alliance capital.

The evidence on the intricate interactions between internal technological capital and alliance capital emphasizes the dominant role of absorptive capacity in early industry development, but suggests that the absorptive capacity argument is much less crucial for performance in mature phases of the technology life cycle. In principle, firms with strong technological capital bases may be better placed to circumvent potential risks of knowledge dissipation and improper partner selection associated with larger alliance portfolios, by evaluating the knowledge of potential allies, by identifying opportunities and complementarities, and by reducing the risks of entering into inapprbopriate inter-organizational collaborations (Prabhu, Chandy and Ellis, 2005). However, our findings suggest that selection capabilities are a more salient force in early stages of the technology life cycle under uncertain and rapid technology developments. To shed further light on this issue, future work should take into account organizational factors in order to improve our understanding of the interaction between technological capital and alliance portfolios (Lane and Lubatkin, 1998; Zahra and George, 2002; Todorova and Durisin, 2007). Firms might be able to overcome the negative effects of combined alliance and technological capital if they have invested resources in alliance capabilities in their organization. Alliance capabilities are defined 'as the organizational ability to manage a comprehensive alliance portfolio successfully' (Hoffmann, 2005, p.123). Overall, being equipped with a variety of alliance management skills is critical in enabling firms to manage their alliance networks efficiently.

The current study has a number of managerial implications. As external technology sourcing becomes more and more important, innovating firms have increasingly been involved in establishing alliances and alliance portfolios. Managers can decrease R&D costs and risks, shorten time to market, and get access to emerging technologies through alliances or other technology sourcing modes. Sourcing or co-development of technological innovations through alliances has usually been considered as a management practice with positive effects on the innovation performance and bottom-line of companies. Our research shows that alliance portfolios generate the strongest effect on technology performance of companies with world-class technological skills and extensive patent portfolios in the early stages of the ASIC industry. Combining internal and external technology is particularly important to deal with the technological turbulence surrounding firms operating in the early stages of high-tech sectors. Alliances strategies, as they have been analyzed and prescribed in the past (Bamford et al., 2003; Doz and Hamel, 1998) may generate the largest benefits for companies with the strongest patent portfolios in emerging high tech industries. Our findings also imply that the management of individual alliances should be coordinated in a portfolio approach and should be integrated with technology management (Gomes-Casseres, 1996; Bamford *et al.*, 2003). Alliance portfolio management and technology management have to be aligned, since the resulting technology performance of a company is determined by the joint effect of alliance networks and internal technology capabilities, as well as by the stage of technology life cycle (Heimeriks *et al.*, 2007; Kale and Singh, 1999; Kale et al. 2000).

Our results suggest that differences in technological performance between ASIC firms result to an important extent from the way they are combining investments in both internal technology development and the sourcing of externally developed technology in specific phases of industry development. While extant research has paid substantial attention to technology life cycles (Abernathy and Utterback, 1978; Andersen, 1999; Schmoch, 2007; Breschi et al., 2000), this literature has mostly focused on identifying and measuring technology cycles, or varying patterns of entry, exit and growth across industry cycles. Our research suggests that the role and influence of open innovation and external knowledge sourcing strategies may differ importantly across the phases of industry and technology development. Future research should further explore these relationships, while clarifying to what extent the results can be confirmed in other high technology industry settings than the ASIC industry.

Other limitations of our study suggest interesting possibilities for future research. One possibility is to examine in detail the characteristics of alliance networks and how these change over the technology life cycle. Network characteristics such as redundancy or the existence of structural holes (Burt, 1992; Coleman 1988, 1990; Baum et al., 2000; Ahuja, 2000b) may interact with the technological capabilities of alliance partners to impact the effectiveness of alliance capital. In addition, (Nooteboom *et al.*, 2007) has shown that the innovation performance of firms is not only determined by the technological capital of the focal firm and that of its partners but also by the technological distance between them as this shapes the learning opportunities within alliances. An analysis on the dyadic level could also explore whether the formation of new alliances is affected differently by the existing technological capital of the partnering companies depending on the stage of the technology life cycle.

While we weighted patents by the citations they receive, patents may be valued differently by innovating firms as they are interested in deepening their core technologies as well as in exploring new and promising technologies. In line with the seminal paper of March (1991) several scholars have analyzed technology alliances in terms of exploration and exploitation (Faems *et al.*, 2005; Lavie and Rosenkopf, 2006; Rothaermel and Deeds, 2004; Schildt *et al.*, 2005; Vanhaverbeke *et al.*, 2012; Raisch et al, 2009; Lavie et al, 2011). The combined role of the technological and alliance capital on deepening existing technologies and exploring new technological areas is a further area for exploration. Is a firm's existing technological capital an asset or a liability in exploring new technologies? Do companies require different technology alliance networks over time to deepen the existing technologies and to explore new technologies? The answer to these questions may again be related to the concept of technology life cycles characterizing high tech industries. This suggests a challenging agenda for future research.

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Table 1: ASIC definitions

I. ***Semicustom IC:*** A monolithic circuit that has one or more customized mask layers, but does not have all mask layers customized, and is sold to only one customer.

> **Gate arrays:** A monolithic IC usually composed of columns and rows of transistors. One or more layers of metal interconnect and are used to customize the chip.
>
> **Linear array:** An array of transistors and resistors that performs the functions of several linear ICs and discrete devices.

II. ***Custom IC:*** A monolithic circuit that is customized on all mask layers and is sold to only one customer.

> **Standard cell IC:** A monolithic circuit that is customized on all mask layers using a cell library that embodies pre-characterized circuit structures.
>
> **Full custom IC:** A monolithic circuit that is at least partially "handcrafted". Handcrafting refers to custom layout and connection work that is accomplished without the aid of standard cells.

III. ***Programmable Logic Device (PLD):*** A monolithic circuit with fuse, antifuse, or memory cell-based logic that may be programmed (customized), and in some cases, reprogrammed by the user. **Field Programmable Gate Array (FPGA):** A PLD that offers fully flexible interconnects, fully flexible logic arrays, and requires functional placement and routing.

Electrically Programmable Analog Circuit (EPAC): A PLD that allows the user to program and reprogram basic analog devices.

Table 2: Definitions of dependent and independent variables

Variable name	Variable description	Hypothesized effects
Technological performance	Count of the citation weighted number of ASIC-related patents successfully applied for in the current year (t). Dependent variable.	Dep. Var.
Technological capital	Count of the citation weighted number of ASIC-related patents successfully applied for by the firm in the previous five years (t-5 to t-1); divided by 1000,	H1: Positive
Alliance capital	Number of technology alliances established by the firm in the five previous years (t-5 to t-1) unless alliances were terminated earlier	H2: Positive
Alliance capital^2	Squared term of alliance capital	H2: Negative
Alliance capital * technological capital	Interaction between alliance capital and technological capital	H3: Positive
Alliance capital * technological capital* trend term	Interaction between alliance capital, technological capital and trend term (taking values 0 in 1987 up to 13 in 2000)	H3: Negative
Technological performance of alliance partners	Sum of the patent citations received by the firm's alliance partners, as defined under alliance capital, divided by 1000	
R&D intensity	Natural logarithm of the ratio of R&D expenditures over total sales, t-1,	
Firm size	Natural logarithm of the ASIC sales of the firm, t-1	
Captive producer	Dummy variable denoting that the firm is not selling ASICs on the market	
Asian Firm	Dummy variable denoting that the firm is headquartered in Asia	
European Firm	Dummy variable denoting that the firm is headquartered in Europe	
GA-producer	Dummy variable denoting that the firm is producing only gate arrays	
SC-producer	Dummy variable denoting that the firm is producing only standard cells	
PLD-producer	Dummy variable denoting that the firm is producing only PLDs	
GA and SC producer	Dummy variable denoting that the firm is producing gate arrays and standard cells	
GA and PLD producer	Dummy variable denoting that the firm is producing gate arrays and PLDs	

Table 3: Descriptive statistics and correlation matrix (N=1190)

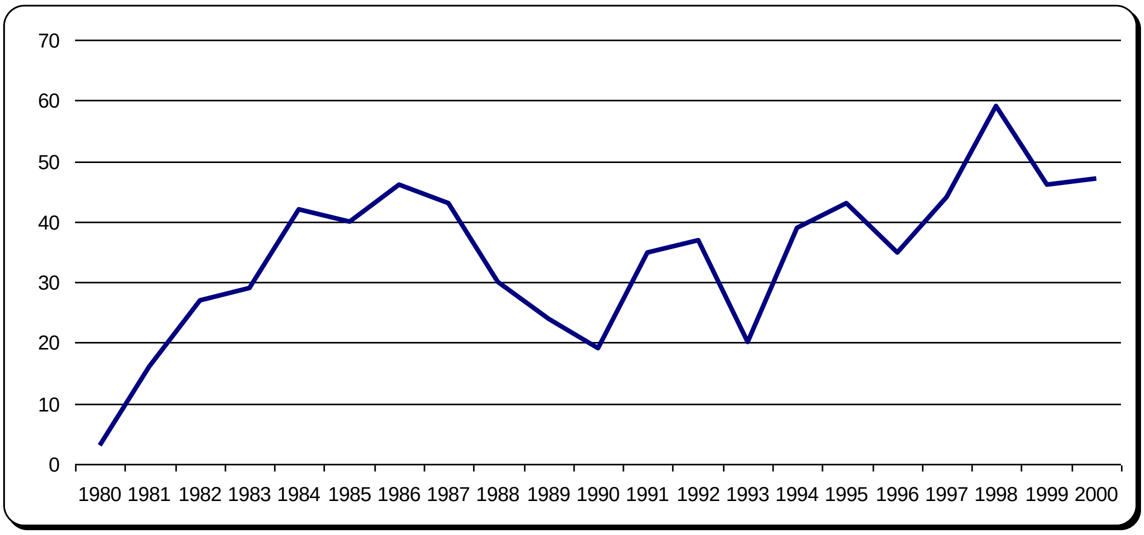
		Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Technological perfomance	54.28	154.64																
2	Technological capital	89.87	303.97	0.96															
3	Alliance capital	14.03	15.86	0.16	0.14														
4	Alliance capital^2	448.22	865.87	0.07	0.07	0.93													
5	Alliance capital * technological capital	1.93	5.78	0.89	0.90	0.34	0.28												
6	Technological performance all. partners	4.07	3.21	0.24	0.22	0.66	0.47	0.30											
7	R&D intensity (ln)	4.66	2.42	-0.02	-0.00	0.39	0.33	0.06	0.41										
8	Firm size (ln)	3.92	1.52	0.26	0.28	0.49	0.38	0.35	0.48	0.59									
9	Captive producer	0.05	0.23	-0.07	-0.07	-0.06	-0.05	-0.08	-0.05	0.21	-0.20								
10	Firm is Asian	0.25	0.43	-0.10	-0.10	-0.10	-0.13	-0.12	0.10	0.43	0.32	-0.05							
11	Firm is European	0.15	0.36	-0.10	-0.10	0.24	0.27	-0.07	0.07	0.16	-0.04	0.06	-0.25						
12	GA-producer	0.19	0.40	-0.14	-0.14	-0.36	-0.24	-0.16	-0.32	-0.33	-0.40	0.09	-0.20	-0.12					
13	SC-producer	0.19	0.39	-0.12	-0.11	-0.13	-0.12	-0.10	-0.23	-0.19	-0.25	0.02	-0.20	0.18	-0.24				
14	PLD-producer	0.12	0.32	0.49	0.47	-0.03	-0.09	0.40	0.16	-0.29	-0.01	-0.09	-0.21	-0.16	-0.18	-0.18			
15	GA and SC producer	0.36	0.48	-0.13	-0.12	0.09	0.03	-0.13	0.18	0.43	0.37	0.04	0.48	-0.01	-0.37	-0.31	-0.36		
16	GA and PLD producer	0.01	0.14	0.06	0.03	0.16	0.15	0.10	0.09	0.06	0.01	-0.03	-0.08	0.09	-0.07	-0.05	-0.07	-0.10	
17	SC and PLD producer	0.01	0.10	0.00	-0.00	0.09	0.05	0.00	0.12	0.06	-0.02	-0.02	-0.06	-0.04	-0.05	-0.04	-0.05	-0.07	-0.01

Table 4: Random effects negative binomial analysis of the technological performance (citation weighted patents) of ASIC producers: 1988-2000.

	Model 1	Model 2	Model 3	Model 4	Model 5
Technological capital		0.282***	0.270***	0.506***	0.795***
		[0.057]	[0.057]	[0.115]	[0.126]
Alliance capital			0.298***	0.307***	0.256***
			[0.047]	[0.049]	[0.052]
Alliance capital squared			-0.013***	-0.011***	-0.008**
			[0.003]	[0.003]	[0.004]
Alliance capital * technological capital				-0.061**	0.167***
				[0.027]	[0.044]
All. capital * techn. Capital * trend (1988-2000)					-0.027***
					[0.005]
Technological performance of alliance partners	0.139***	0.160***	0.075**	0.077**	0.080**
	[0.031]	[0.031]	[0.035]	[0.036]	[0.036]
R&D intensity	0.326***	0.321***	0.280***	0.282***	0.304***
	[0.042]	[0.042]	[0.041]	[0.041]	[0.042]
Firm size	0.286***	0.237***	0.162***	0.164***	0.158***
	[0.042]	[0.043]	[0.041]	[0.042]	[0.041]
PLD-producer	1.786***	1.505***	1.871***	1.955***	1.956***
	[0.232]	[0.242]	[0.240]	[0.245]	[0.243]
GA-producer	-0.767***	-0.804***	-0,225	-0,134	-0,1
	[0.274]	[0.272]	[0.278]	[0.282]	[0.279]
SC-producer	-0.521**	-0.591***	-0,197	-0,081	-0,032
	[0.230]	[0.228]	[0.229]	[0.238]	[0.236]
GA and SC producer	-0,234	-0,241	-0,016	0,017	0,057
	[0.164]	[0.163]	[0.161]	[0.163]	[0.161]
GA and PLD producer	2.141***	1.960***	2.248***	2.283***	1.917***
	[0.268]	[0.268]	[0.264]	[0.266]	[0.273]
SC and PLD producer	0,401	0,26	0,173	0,205	0,001
	[0.471]	[0.468]	[0.450]	[0.448]	[0.442]
Captive producer	0,263	0,113	0,124	0,114	0,043
	[0.241]	[0.238]	[0.227]	[0.227]	[0.227]
Firm is European	-0.981***	-0.941***	-1.209***	-1.283***	-1.197***
	[0.203]	[0.199]	[0.200]	[0.203]	[0.196]
Firm is Asian	-0,163	-0,131	0,23	0,249	0,186
	[0.165]	[0.164]	[0.168]	[0.169]	[0.168]
constant and year dummies	included	included	included	included	included
Observations	1190	1190	1190	1190	1190
number of firms	117	117	117	117	117
Wald Chi square test	509.30***	604.24***	705.31***	700.62***	815.64***
Loglikelihood	-2810	-2800	-2773	-2770	-2756

Notes: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$ (two sided tests). Standard deviations in parentheses.

Figure 1: Cooperative R&D activities in the ASIC-Industry (1980-2000)



Figures 2a and 2b: The Impact of alliance capital and technological capital on technological performance: 1987 (2a) and 2000 (2b)

Figure 2a

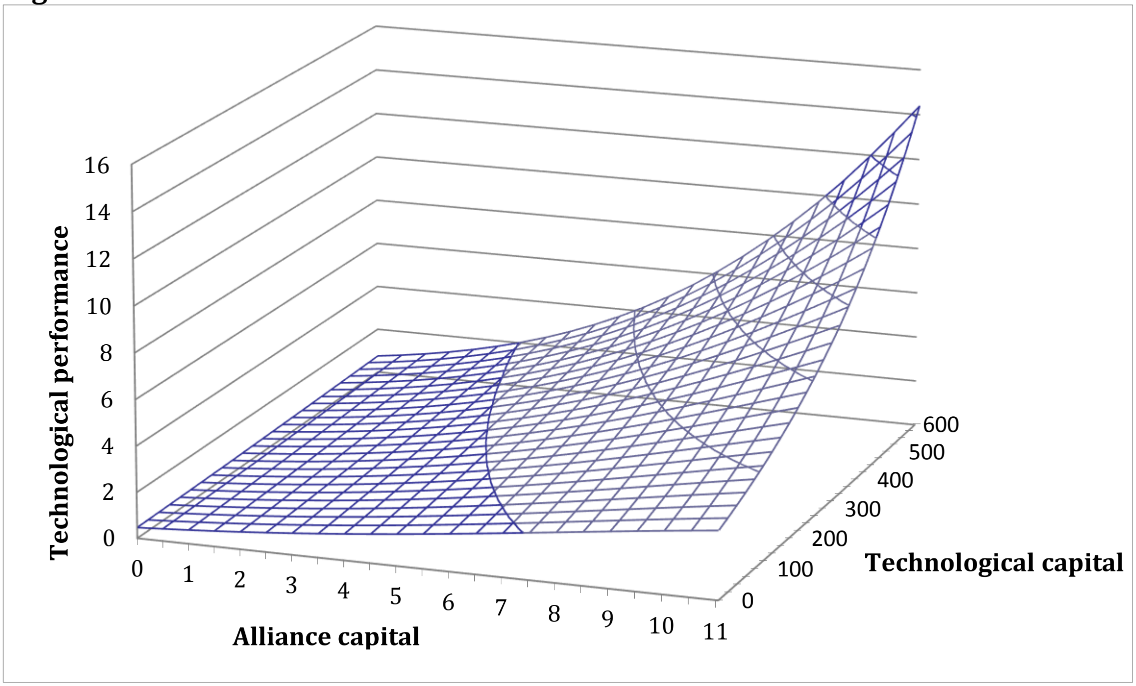
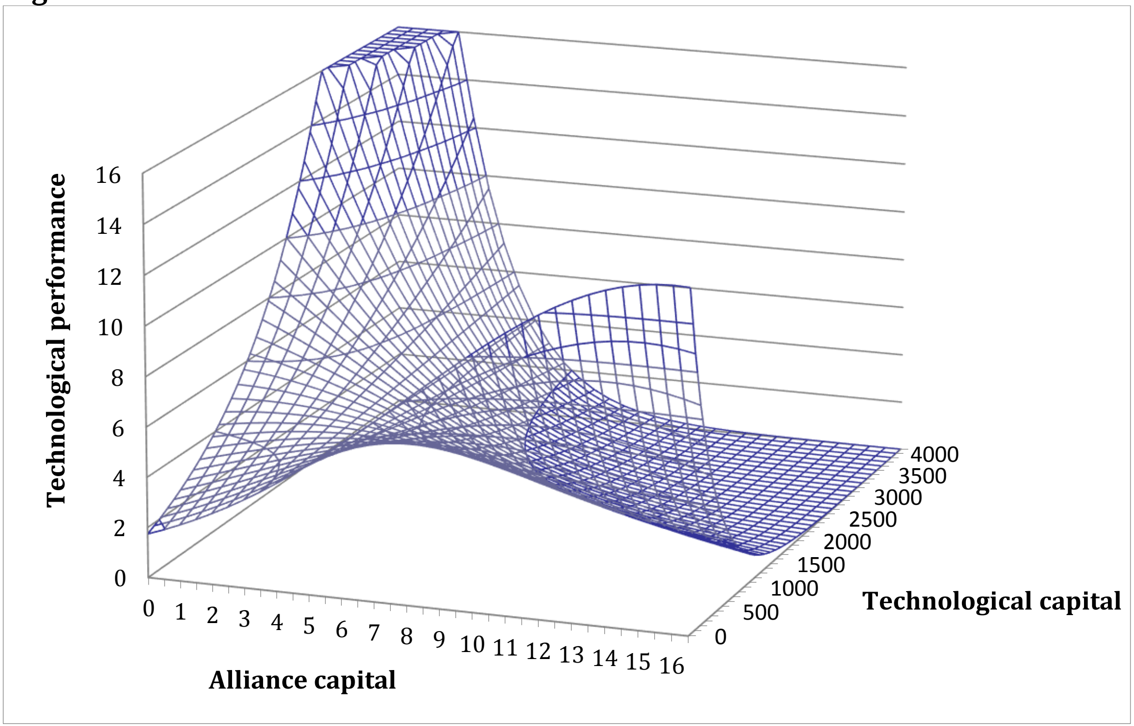


Figure 2b



Note: the displayed range of technological performance is set equal to Figure 2a. For the highest levels of Technological capital in the absence of alliances, the predicted technological performance exceeds this scale.

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